II. REMARKS

Claims 26 and 27 have been canceled without prejudice, and new independent claims 28 and 29 have been added. In particular, new independent claim 28 corresponds to previous dependent claim 26, but rewritten in independent form. Thus, new independent claim 28 has the same scope as previous claim 26. New independent claim 29 corresponds to previous claim 27, but rewritten in independent form. Consequently, new independent claim 29 has the same scope as previous claim 27.

The present amendment adds no new matter to the instant application, and raises no new issues.

A. The Invention

The present invention pertains broadly to a timepiece, such as would have a microgenerator for powering various electronic and/or mechanical components of the timepiece. A first embodiment in accordance with the present invention is a timepiece having the features recited in claim 1. A second embodiment in accordance with the present invention is a timepiece having the features recited in claim 23. A third embodiment in accordance with the present invention is a timepiece having the features recited in claim 28. A fourth embodiment in accordance with the present invention is a timepiece having the features recited in claim 29. Various other embodiments in accordance with the present invention are recited in the dependent claims.

All of the embodiments, in accordance with the present invention, relate to a timepiece having "an electronic module including a support with conductive paths" wherein certain conductive paths are "made of essentially non-magnetic material

selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy." The phrase "non-magnetic material" has a specific definition as provided on page 1, lines 8-10, of the present application. Because the conductive paths are "made of essentially non-magnetic material," they do not generate an opposing magnetic field when in proximity to an operating functional unit including magnetized masses. Consequently, the conducting paths of the timepiece, in accordance with the present invention, do not act to brake the operation of the functional unit.

B. The Rejections

Claims 1-3, 5-17 and 20-25 stand rejected under 35 U.S.C. § 103(a) as unpatentable over Schafroth (U.S. Patent 6,124,649) in view of Applicants' Admitted Prior Art (Applicants' specification, at 2) and Lin (U.S. Patent 4,176,362).

Applicants respectfully traverse the rejection and request reconsideration of the application for the following reasons.

C. Applicants' Arguments

A patentability analysis under 35 U.S.C. § 103 requires (a) determining the scope and content of the prior art, (b) ascertaining the differences between the prior art and the claimed subject matter, (c) resolving the level of ordinary skill in the pertinent art, and (d) considering secondary considerations that may serve as indicia of nonobviousness or obviousness. Graham v. John Deere Co. of Kansas City, 148 U.S.P.Q. 459, 467 (1966). Furthermore, a proper rejection under Section 103 further requires showing (1) that the

prior art would have suggested to a person of ordinary skill in the art that they should make the claimed device or carry out the claimed process, (2) that the prior art would have revealed to a person of ordinary skill in the art that in so making or doing, there would have been a reasonable expectation of success, and (3) both the suggestion and the reasonable expectation of success must be found in the prior art and not in the applicants' disclosure. In re Vaeck, 20 U.S.P.Q.2d 1438, 1442 (Fed. Cir. 1991).

In the present case, the scope and content taught by the references relied upon by the Examiner is insufficient to establish a prima facie case of obviousness because the references fail to teach, or suggest, "essentially non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy" as recited in independent claims 1, 23, 28 and 29.

i. The Schafroth Patent

U.S. Patent 6,124,649 to Schafroth (hereafter, the Schafroth Patent) teaches a "micro-generator module and clockwork movement containing such a micro-generator" as shown in Figures 1 and 2. The Schafroth Patent teaches that the micro-generator includes a shaft (10) connected to a rotor, wherein the rotor includes an upper disk (11) and a lower disk (13). The disks (11) and (13) are made of sheet metal with high saturation (i.e., remanence about 2.4 Tesla), (col. 2, lines 58-62). Each disk (11) and (13) has six individual magnets glued thereon and disposed with north-south-north alternating polarity. A spring (not shown) drives seconds-wheel (71) mounted on seconds-arbor (70), and the seconds-wheel (71) drives first intermediate pinion (60) which, in turn, drives second intermediate pinion (50), (col. 2, lines 26-50). The second

intermediate pinion (50) and its arbor are made of non-magnetic material such as copper-beryllium alloy (col. 2, lines 41-45).

The Schafroth Patent further teaches an electronic module (80) equipped with a micro-generator as shown in Figure 2, wherein the module includes three coils (20), (21) and (22) mounted between disks (11) and (13) and disposed so there is a space (18) between coils (20) and (21). This asymmetric arrangement of coils (20), (21) and (22) with respect to shaft (10) of the rotor makes it possible to mount the rotor after coils (20), (21) and (22) have been glued to the module (80), (col. 4, lines 54-63). An integrated circuit (81) is mounted on module (80) and is connected to monitor the rotational speed of the micro-generator and to adjust this speed by changing the value of a variable load resistor (col. 3, lines 60-64). The circuit includes a voltage tripler that uses three capacitors (82), (83) and (84), which are mounted to the module (80) outside of the integrated circuit (81).

The Schafroth Patent teaches that coils (20) and (22) are soldered or glued to the module (80) at point of connection (801), coils (21) and (22) are soldered or bonded to the module (80) at point of connection (802), coil (20) is soldered or bonded to point of connection (800), and coil (21) is soldered or bonded to point of connection (803). Thus, the Schafroth Patent teaches that the coils (20), (21) and (22) are connected in series between the points (800), (801), (802) and (803) so voltages produced by the coils are added (col. 3, lines 49-60). As shown by Figure 2, points (800), (801), (802) and (803) are connected by conducting paths on the printed circuit, which were made using conventional print circuit technology (col. 3, lines 54-60).

As admitted by the Examiner (Office Action, dated March 25, 2005, at 3, line 24, to at 25, line 2; and Office Action, dated May 11, 2004, at 3, line 23, to at 4, line 2), the Schafroth Patent fails to teach, or even suggest, the "conductive paths...made of essentially non-magnetic material" as recited in claims 1, 23, 28 and 29, the "conductive paths include a protective layer formed of a non-magnetic material selected from the group consisting of <u>a nickel based alloy containing phosphorous</u> and <u>a palladium based alloy</u>" as recited in claim 1 and 29; that "said conductive paths include an adherence underlayer formed of a non-magnetic material" as recited in claims 7 and 8; and the "adherence underlayer is made of a nickel based alloy" as recited in claims 10 and 11 of the present application. Furthermore, the Schafroth Patent does not teach, or event suggest, the "<u>conductive paths</u> disposed in proximity to the microgenerator <u>are non-magnetic</u>... and <u>do not brake the microgenerator</u>" as recited in independent claims 28 and 29.

ii. <u>Applicants' Admitted Prior Art</u>

Applicants' specification, on page 2, line 29, to page 3, line 4, teaches that electrically conductive paths are typically made in two steps. First, a layer of very good conductive material, such as copper or gold based alloy, is deposited on the substrate (Applicants' specification, at 2, lines 30-31). Copper and gold are non-magnetic metals (Applicants' specification, at 3, lines 9-10). In a second step, a fine protective layer of a nickel based alloy, <u>which has good resistance to oxidisation and has ferromagnetic properties</u>, is deposited on the conductive layer (Applicants' specification, at 2, lines 31-33, and at 3, lines 3-4). Sometimes, an underlayer is

deposited before depositing the conductive layer to improve adherence of the conductive layer to the substrate, and the underlayer is made of a nickel based alloy (Applicants' specification, at 2, lines 33-36).

Applicants' Admitted Prior Art fails to teach, or even suggest, that "at least those conductive paths located in proximity to said functional unit are made of essentially non-magnetic material" as recited in claims 1, 23, 28 and 29; "a protective layer formed of a non-magnetic material selected from the group consisting of <u>a nickel based alloy containing phosphorous</u> and <u>a palladium based alloy</u>" as recited in claims 1, 23 and 29; an "underlayer formed of a non-magnetic material" as recited in claims 7 and 8; and "wherein <u>the conductive paths</u> disposed in proximity to the microgenerator are <u>non-magnetic</u>... and <u>do not brake the microgenerator</u>" as recited in claims 28 and 29.

iii. <u>The Lin Patent</u>

U.S. Patent 6,562,709 B1 to Lin (hereafter, the Lin Patent) teaches a "semiconductor chip assembly with simultaneously electroplated contact terminal and connection joint," such as shown in Figure 1G, which is made using the method illustrated by Figures 3A to 3G. However, the Lin Patent also teaches that a conductive trace, contact terminal and connection joint can be various conductive materials including copper, gold, nickel, palladium, tin, and combinations thereof, and alloys thereof (col. 11, lines 46-57). The Lin Patent also teaches that it is generally desirable to protect electroplated copper with another electroplated metal such as nickel, palladium or gold (col. 11, lines 57-59). However, <u>the Lin Patent is silent regarding the</u>

ferromagnetic properties of the metals nickel, palladium and gold employed to protect the electroplated copper.

Consequently, the Lin Patent does not teach, or even suggest, a "timepiece ...wherein at least those conductive paths located in proximity to said functional unit are made of essentially non-magnetic material, wherein the conductive paths include a protective layer formed of a non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy" as recited in claims 1 and 29 of the present application. Furthermore, the Lin Patent does not teach, or suggest, an "adherence underlayer is made of a nickel based alloy" as recited in claims 10 and 11.

The Lin Patent also does not teach, or even suggest, that (i) "the conductive paths are made of essentially non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy" and (ii) "wherein conductive paths disposed in proximity to the microgenerator... do not disturb operation of the microgenerator" as recited in claim 23 and 28. The Lin Patent also does not teach, or even suggest, that "the conductive paths disposed in proximity to the microgenerator are non-magnetic... and do not brake the microgenerator" as recited in claims 28 and 29.

iv. Summary of the Art

The Schafroth Patent teaches a clockwork movement containing a micro-generator connected by conducting paths to various points and to an integrated circuit on a printed circuit.

The Applicants' Admitted Prior Art teaches that a conductive path may include three layers on a substrate as follows: (1) an underlayer made of nickel based alloy deposited on the substrate, (2) a conductive layer made of a conductive material such as copper or gold based alloy, and (3) a protective layer made of ferromagnetic nickel based alloy. Applicants' Admitted Prior Art also teaches that gold and copper are non-magnetic metals.

The Lin Patent teaches that a conductive trace can be various conductive materials including copper, gold, nickel, palladium, tin, and combinations thereof, and alloys thereof. The Lin Patent additionally teaches that when the conductive material is electroplated copper, then a protective layer of electroplated metal, such as nickel, palladium or gold, is desirable. However, the Lin Patent is silent regarding the ferromagnetic or magnetic properties of nickel, palladium or gold.

As is plain from the scope and content of the Art relied upon by the Examiner, neither the Schafroth Patent, Applicants' Admitted Prior Art, nor the Lin Patent teach, or even suggest, (i) a protective layer formed of a non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy as recited in claims 1 and 29, and (ii) an adherence underlayer formed of a non-magnetic nickel based alloy as recited in claims 10 and 11.

As conceded by the Examiner (See Examiner's Interview Summary of July 12, 2005, at 3), neither the Schafroth Patent, the Applicants' Admitted Prior Art, nor the Lin Patent teach, or even suggest, (iv) "conductive paths...made of essentially non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy, and wherein conductive paths disposed in

proximity to the microgenerator ...do not disturb operation of the microgenerator" as recited in claims 23 and 28, and (v) "the conductive paths include a protective layer formed of a non-magnetic material selected from the group consisting of <u>a nickel based alloy containing phosphorous</u> and <u>a palladium based alloy</u>" as recited in claim 1 of the present application.

Furthermore, neither the Schafroth Patent, Applicants' Admitted Prior Art, nor the Lin Patent teach, or even suggest, "the <u>conductive paths</u> disposed in proximity to the microgenerator <u>are non-magnetic</u>... <u>and do not brake the microgenerator</u>" as recited in claims 28 and 29.

v. <u>Reply to Examiner's Arguments</u>

The Examiner contends Applicants have acknowledged that Schafroth teaches the use of non-magnetic materials with the watch drive (See Office Action, dated October 31, 2005, at 4, lines 1-2). Applicants have made no such acknowledgement with respect to the "conductive paths," which is the subject matter of the present invention. It is irrelevant whether other parts of a timepiece may be constructed of a non-magnetic material (e.g., glass or plastic) because not all non-magnetic materials are suitable for constructing "conductive paths." The Examiner has not shown a motivation, grounded in the Schafroth reference, to suggest making a "conductive path" out of a non-magnetic material. It does not matter whether other components of the timepiece are made of non-magnetic material when these other components are not used to conduct electrical power.

The Examiner contends that the Lin Patent teaches making conductive paths using non-magnetic materials and cites col. 11, lines 47-59 (See Office Action, dated October 31, 2005, at 4, lines 2-4). The Examiner misconstrues the teachings of the Lin Patent. It is a well-settled proposition that an Examiner must give a fair reading of what a reference teaches as a whole. In re Gordon, 221 U.S.P.Q.2d 1125, 1127 (Fed. Cir. 1987).

In the present case, the Lin Patent does not teach, or suggest, making a "conductive path" of "essentially non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorus and a palladium based alloy" as recited by independent claims 1, 23, 28 and 28. In fact, none of the references cited by the Examiner teach, or suggest, "a nickel based alloy **containing phosphorous**" as recited in the claims. Furthermore, none of the references cited by the Examiner teach, or suggest, "a palladium based alloy" as recited in the claims. For this reason alone, the Examiner's rejection is untenable and must be withdrawn.

However, this is not the only error in the Examiner's reading of the Lin Patent. The Lin Patent, when taken as a whole, teaches making a conductive trace, contact terminal, and connection joint out of materials having low resistivity and cost (col. 11, lines 46-59). The Lin Patent does not teach, or even recognize, selecting materials for constructing a conductive trace to ensure that the conductive trace is "non-magnetic" in accordance with the present invention. Thus, it is clear that neither the Lin Patent, or any other reference relied upon by the Examiner, teaches making "conductive paths" from "nickel based alloys containing phosphorous" and from "palladium based alloys" as recited in the instant claims.

Lastly, when interpreting the language of the instant claims and the teachings of the Schafroth and Lin references, the Examiner has not properly construed the term "essentially non-magnetic material." In the specification as originally filed, "non-magnetic" is used to describe materials that "do not have ferromagnetic properties" (See Specification, page 3, lines 16-18). A person of ordinary skill in the art would recognize that materials may be classified as ferromagnetic, paramagnetic or diamagnetic (See, e.g., HANS C. OHANIAN, PHYSICS (1985), pp. 738-749, and a copy of the cited pages are filed herewith). Ferromagnetic materials have a relative permeability constant $\kappa_m >> 1$, paramagnetic materials have $\kappa_m > 1$, and diamagnetic materials have $\kappa_m < 1$ (See, e.g., HANS C. OHANIAN, PHYSICS (1985), p. 749).

Applicants specification further describes that nickel based alloys conventionally used to make conductive paths are ferromagnetic, but that certain nickel based alloys containing phosphorous and palladium based alloys are "non-magnetic" (See Specification, page 3, lines 19-22). In the context of Applicants' disclosure, a person of ordinary skill in the art would realize that a "non-magnetic material" and "conductive paths" that are "non-magnetic" are structures having paramagnetic or diamagnetic properties, but not ferromagnetic properties.

To further define the magnitude of the "non-magnetic" feature of the "conductive paths," claims 28 and 29 recite that "the conductive paths disposed in proximity to the microgenerator <u>are non-magnetic... and do not brake the microgenerator.</u>" As is clear from the language of claims 28 and 29, it is the "conductive paths" as a whole that "are non-magnetic" and that have non-magnetic properties (i.e., paramagnetic or diamagnetic properties) so as not to "brake the

microgenerator." The Examiner has failed to properly construe the language of claims 28 and 29. This misinterpretation is plain in view of the fact the Examiner relies upon the ferromagnetic nickel based alloy described on page 2, lines 29, to page 3, line 4, of Applicants' disclosure in making the present rejection.

In short, the Examiner has failed to show that the references teach the claimed "nickel based alloy containing phosphorous" and the "palladium based alloy" as recited in claims 1, 23, 28 and 29, and the Examiner has failed to show that the references teach "conductive paths" that "are non-magnetic...and do not brake the microgenerator" as recited in claims 28 and 29. Furthermore, even if the references did teach similar materials (which they do not) as those recited in the instant claims, the Examiner has failed to show a motivation, suggestion, incentive or teaching grounded in the references, and not Applicants' disclosure, for picking and choosing from among the various materials, most of which are plainly ferromagnetic, taught by the references to arrive at Applicants' claimed invention. See In re Vaeck, 20 U.S.P.Q.2d 1438, 1442 (Fed. Cir. 1991)("the suggestion...must be founded in the prior art, not in applicant's disclosure); and Northern Telecom, Inc. v. Datapoint Corporation, 15 U.S.P.Q.2d 1321, 1323 (Fed. Cir. 1990)('individual references can not be "employed as a mosaic to recreate a facsimile of the claimed invention."').

For all of the above reasons, the Examiner has not established a proper prima facie case of obviousness against the presently claimed invention.

III. CONCLUSION

The rejection of claims 1, 5-8, 10-17, 20-23, 26 and 27 under 35 U.S.C. § 103(a) is untenable and must be withdrawn because the scope and content provided by the Schafroth Patent, Applicant's Admitted Prior Art, and the Lin Patent, is insufficient to support the Examiner's obviousness rejection. Specifically, none of these references teach, or even suggest, (i) conductive paths that include "a protective layer formed of a non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy" as recited in independent claims 1 and 29; conductive paths "made of essentially non-magnetic material selected from the group consisting of a nickel based alloy containing phosphorous and a palladium based alloy" as recited in claims 23 and 28; and "wherein the conductive paths disposed in proximity to the microgenerator are non-magnetic ...and do not brake the microgenerator" as recited in claims 28 and 29.

For all of the above reasons, claims 1, 5-8, 10-17, 20-23, 28 and 29 are in condition for allowance, and a prompt notice of allowance is earnestly solicited.

Questions are welcomed by the below signed attorney of record for the Applicants.

Respectfully submitted,

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CHAPTER 33

Magnetic Materials

Within the atom and the nucleus, charged particles are continually moving about — electrons orbit around the nucleus and protons orbit around each other inside the nucleus. The orbital motions may be regarded as flows of electric currents within the atom, and these currents generate magnetic fields. Besides their orbital motions, the charged particles within atoms have rotational motions — electrons, protons, and neutrons all spin about their axes. The rotational motions may be regarded as flows of electric currents inside the particles, and these currents also generate magnetic fields.

The magnetic fields arising from currents flowing in loops inside atoms, nuclei, and particles can be described in terms of the corresponding magnetic dipole moments. If many of these small dipole moments within a sample of material are aligned, they will produce a strong magnetic field. Such an alignment can be achieved by placing the sample of material in the magnetic field of, say, an electromagnet. The magnetic field produced by the atomic and subatomic currents will then be strong, and it will modify the original magnetic field produced by the currents in the windings of the electromagnet. For instance, if a piece of iron is placed between the poles of an electromagnet, the magnetic field is strengthened drastically — it may become several thousand times stronger than the original magnetic field. Exactly how much the original magnetic field is increased or decreased depends on the response of the atomic and subatomic dipoles to the original magnetic field. According to the nature of their magnetic response, we can classify materials as paramagnetic, ferromagnetic, or diamagnetic. Before we discuss these types of magnetic materials, we will take a brief look at the magnitudes of the magnetic moments contributed by electrons, protons, and neutrons.

33.1 Atomic and Nuclear Magnetic Moments

An electron moving in an orbit around a nucleus produces an average current along its orbit. Strictly, the calculation of atomic orbits and currents requires quantum mechanics; but for the sake of simplicity, let us do this calculation with classical mechanics. If the electron has a circular orbit with radius r and speed v (Figure 33.1), then the time for one complete circular motion is $2\pi r/v$. The charge moved in this time is e and hence the average current along the orbit is

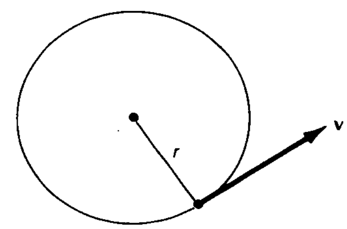


Fig. 33.1 Electron in a circular orbit around a nucleus.

$$I = \frac{e}{2\pi r/v} = \frac{ev}{2\pi r} \tag{1}$$

Such a circulating current will give rise to a magnetic moment [see Eq. (30.44)]

$$\mu = I \times [\text{area}] = \frac{ev}{2\pi r} \times \pi r^2 \tag{2}$$

$$= \frac{evr}{2} \tag{3}$$

In terms of the angular momentum $L = m_e vr$, the magnetic moment can be expressed as[1]

Orbital magnetic moment

$$\boxed{\mu = \frac{e}{2m_e} L} \tag{4}$$

This says that the magnetic moment of an orbiting electric charge is proportional to its angular momentum.

It turns out that the relation (4) is valid not only for circular orbits, but also for any other periodic orbit. Even more important: the relation (4) remains valid when we repeat the calculation using quantum mechanics. The net magnetic moment of the atom is the sum of the magnetic moments of all its electrons. Hence Eq. (4) can also be regarded as a relation between the net orbital angular momentum and the net magnetic moment of the entire atom.

It is a fundamental tenet of quantum mechanics that the magnitude of the orbital angular momentum is always some integral multiple of the constant value $\hbar = 1.06 \times 10^{-34}$ J · s.[2] Thus, the possible values of the orbital angular momentum are[3]

Quantization of angular momentum

$$L = 0, \hbar, 2\hbar, 3\hbar, \ldots \tag{5}$$

Because angular momentum only exists in discrete packets, it is said to

[1] In this equation, the magnetic moment μ must not be confused with the permeability μ_0.

[2] This is Planck's constant divided by 2π, i.e., $\hbar = h/2\pi = 6.63 \times 10^{-34}$ J · s/2π. See Appendix 8 for a more precise value of the constant $\hbar$.

[3] Strictly, these numbers are the possible values for the maximum component of the angular momentum in a chosen direction, say, the z direction.

be **quantized.** The constant $\hbar$ is the fundamental quantum of angular momentum, just as e is the quantum of electric charge. For instance, the oxygen atom has a net orbital angular momentum $L = 1\hbar$ and hence, according to Eq. (4), the orbital magnetic moment is

$$\mu = \frac{e}{2m_e}\hbar = 9.27 \times 10^{-24}\ \mathrm{A \cdot m^2} \tag{6}$$

Besides the magnetic moment generated by the orbital motion of the electrons, we must also take into account that generated by the rotational motion of the electrons. Crudely, an electron may be thought of as a small ball of negative charge rotating about an axis at a fixed rate. The spin, or intrinsic angular momentum, of the electron has a value of $\hbar/2 = 0.53 \times 10^{-34}\ \mathrm{J \cdot s}$. This kind of rotational motion again involves circulating charge and gives the electron a magnetic moment. This intrinsic magnetic moment has a fixed magnitude

Spin magnetic moment

$$\boxed{\mu_{\text{spin}} = \frac{e}{2m_e}\hbar = 9.27 \times 10^{-24}\ \mathrm{A \cdot m^2}} \tag{7}$$

Bohr magneton

which is called a **Bohr magneton.**[4] The direction of this magnetic moment is opposite to the direction of the spin angular momentum (Figure 33.2). Note that Eq. (4) is not valid for the spin magnetic moment. If we were to insert a spin angular momentum of $\hbar/2$ into Eq. (4), we would obtain a magnetic moment $e\hbar/(4m_e)$, one-half the value given by Eq. (7).

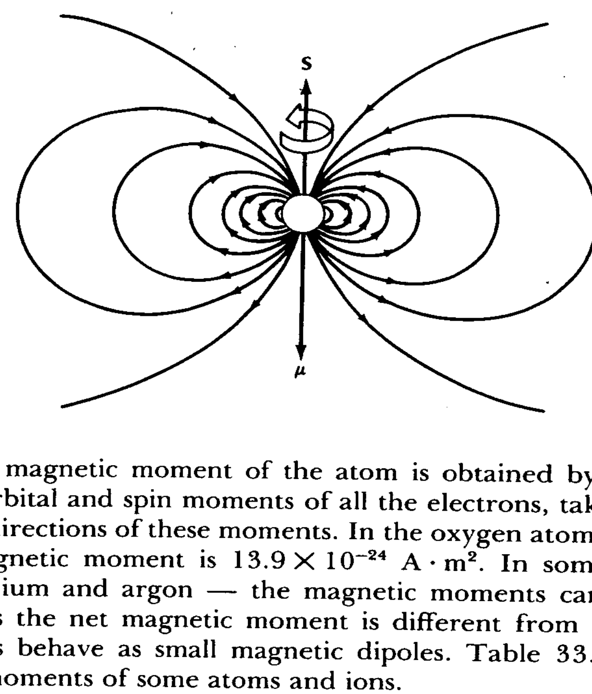


Fig. 33.2 Magnetic field lines of an electron. The magnetic moment μ is opposite to the spin angular momentum **S**.

The net magnetic moment of the atom is obtained by combining both the orbital and spin moments of all the electrons, taking into account the directions of these moments. In the oxygen atom, the net resultant magnetic moment is $13.9 \times 10^{-24}\ \mathrm{A \cdot m^2}$. In some atoms — such as helium and argon — the magnetic moments cancel. But in most atoms the net magnetic moment is different from zero. Thus, most atoms behave as small magnetic dipoles. Table 33.1 gives the magnetic moments of some atoms and ions.

[4] See Appendix 8 for more precise values of the magnetic moments of the elementary particles.

Table 33.1 MAGNETIC MOMENTS OF SOME ATOMS AND IONS

Atom	*Magnetic moment*
H	9.27×10^{-24} A · m^2
He	0
Li	9.27×10^{-24}
O	13.9×10^{-24}
Ne	0
Na	9.27×10^{-24}
Ce^{+++}	19.8×10^{-24}
Yb^{+++}	37.1×10^{-24}

The nucleus of the atom also has a magnetic moment. This is in part due to the orbital motion of the protons inside the nucleus, and in part due to the rotational motion of individual protons and neutrons. The spin of both these particles is $\hbar/2$, the same as that of an electron. The spin magnetic moment of a proton is 1.41×10^{-26} A · m^2 and that of a neutron is 0.97×10^{-26} A · m^2 (the former magnetic moment is parallel to the axis of spin and the latter is antiparallel).[5] The magnetic moment of a proton or a neutron is small compared to that of an electron, and in reckoning the total magnetic moment of an atom, the nucleus can usually be neglected.

33.2 Paramagnetism

The behavior of the magnetic dipoles of the atoms or ions determines whether the material will be paramagnetic, ferromagnetic, or diamagnetic.

In a **paramagnetic material,** the atoms or ions have permanent magnetic dipole moments. When the material is left to itself, these dipoles are randomly oriented and their magnetic fields average to zero. However, if the material is immersed in the magnetic field of, say, an electromagnet, the torque on the dipoles tends to align them with the field (see Section 31.5). This alignment will not be perfect because of the disturbances caused by random thermal motions. But even a partial alignment of the dipoles will have an effect on the magnetic field. The material becomes **magnetized** and contributes an extra magnetic field that *enhances* the original magnetic field.

Paramagnetic material

Magnetization

To see how such an increase of magnetic field comes about, consider a piece of paramagnetic material placed between the poles of an electromagnet. Figure 33.3 shows the alignment of magnetic dipoles in this material; for the sake of simplicity, Figure 33.3b shows a case of perfect alignment. The magnetic dipoles are due to small current loops within the atoms; in Figure 33.4a we see the aligned current loops. Now look at any point inside the magnetic material where two of these current loops (almost) touch. Since the currents at this point are opposite, they cancel. Thus, everywhere inside the material the current is effectively zero. However, at the surface of the material, the current does not cancel. The net result of the alignment of current

[5] See Appendix 8 for more precise values of the magnetic moments of the elementary particles.

Fig. 33.3 (a) A piece of paramagnetic material. In the absence of an external magnetic field, the magnetic dipoles are oriented at random. (b) In the presence of an external magnetic field, the magnetic dipoles align with the magnetic field. The figure shows an ideal case of perfect alignment; in practice, the alignment will only be partial.

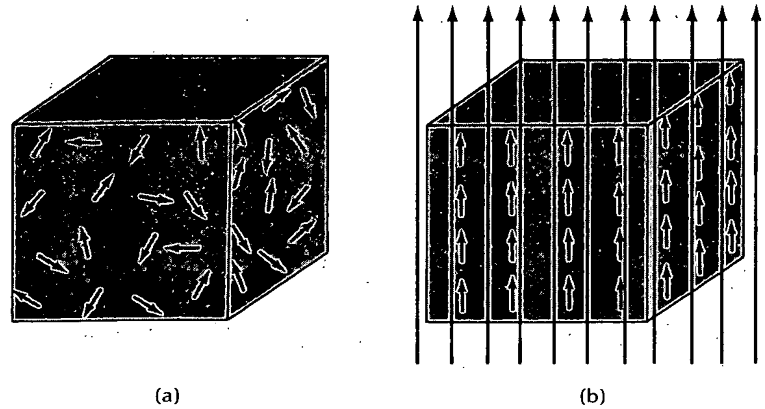
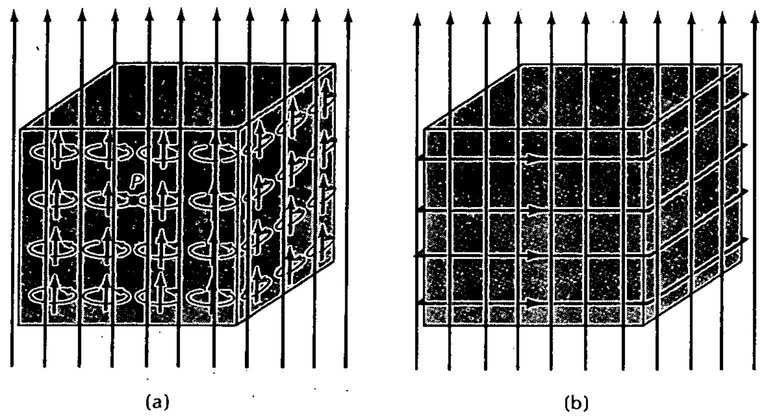


Fig. 33.4 (a) The magnetic dipoles of Figure 33.3b can be regarded as small current loops. At the point *P*, the currents of adjacent loops are opposite, and they cancel. (b) The small aligned current loops of (a) are equivalent to a current along the surface of the piece of material.



loops is therefore a current running along the surface of the magnetized material (Figure 33.4b). The material consequently behaves like a solenoid — it produces an extra magnetic field in its interior. This extra magnetic field has the *same* direction as the original magnetic field (Figure 33.3b). Hence the total magnetic field in a paramagnetic material is larger than the magnetic field produced by the free currents of the electromagnet.

The alignment of the magnetic dipoles in a magnetized paramagnetic material is analogous to the alignment of the electric dipoles in a dielectric material. However, there is a crucial difference: the alignment of magnetic dipoles *increases* the original magnetic field while the alignment of electric dipoles *decreases* the original electric field.

The increase of the strength of the magnetic field by the paramagnetic material can be described by the **relative permeability constant** κ_m. This constant is simply the factor by which the magnetic field is increased. Thus, if the free currents of the electromagnet produce a field B_{free}, then these free currents and the currents in the paramagnetic material acting together produce a field

Relative permeability constant

$$\boxed{\mathbf{B} = \kappa_m \mathbf{B}_{free}} \tag{8}$$

where $\kappa_m > 1$. Table 33.2 lists the values of κ_m for some paramagnetic materials.

Table 33.2 PERMEABILITIES OF SOME PARAMAGNETIC MATERIALS[a]

Material	κ_m
Air	1.000304
Oxygen	1.00133
Oxygen (−190°C, liquid)	1.00327
Manganese chloride	1.00134
Nickel monoxide	1.000675
Manganese	1.000124
Platinum	$1 + 13.8 \times 10^{-6}$
Aluminum	$1 + 8.17 \times 10^{-6}$

[a] At room temperature (20°C) and 1 atm unless otherwise noted.

Just as Gauss' Law in the presence of a dielectric material contains an extra factor κ [see Eq. (27.32)], Ampère's Law in the presence of a paramagnetic material contains an extra factor κ_m. A simple argument shows that the revised form of Ampère's Law is

Ampère's Law in magnetic materials

$$\boxed{\oint \frac{1}{\kappa_m} \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{free}} \qquad (9)$$

If the arrangement of currents and paramagnetic materials is sufficiently symmetric, then we can use Eq. (9) to calculate the magnetic field in the usual way.

EXAMPLE 1. A solenoid filled with air has a magnetic field of 1.20 T in its core. By how much will the magnetic field decrease if the air is pumped out of the core while the current is held constant?

SOLUTION: For air, $\kappa_m = 1.00030$. Hence the magnetic field with air is larger than that without by a factor 1.00030, i.e.,

$$B_{free} = B_{air}/1.00030 \cong B_{air}\,(1 - 0.00030)$$

where we have used the approximation $1/(1 + x) \cong 1 - x$ for small x. The decrease of the magnetic field is then

$$\Delta B = B_{free} - B_{air} = -0.00030 \times 1.20 \text{ T}$$

$$= -3.6 \times 10^{-4} \text{ T}$$

33.3 Ferromagnetism

As is obvious from Table 33.2, the increase of magnetic field produced by a paramagnetic material is quite small. By contrast, the increase produced by a **ferromagnetic material** can be enormous. And what is more, such a material will remain magnetized even if it is not immersed in an external magnetic field. A material that retains magnetization will make a **permanent magnet.**

Ferromagnetic material

Permanent magnet

The intense magnetization in ferromagnetic materials is due to a strong alignment of the spin magnetic moments of electrons. In these

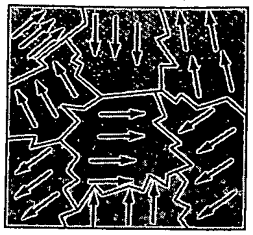


Fig. 33.5 Magnetic domains. Within each domain the magnetic dipoles have perfect alignment.

materials, there exists a special force that couples the spins of the electrons in adjacent atoms in the crystal, a force created by some subtle quantum-mechanical effects (which we cannot discuss here). This spin–spin force tends to lock the spins of the electrons in a parallel configuration. This force acts in the crystals of only five chemical elements: iron, cobalt, nickel, dysprosium, and gadolinium; however, it also acts in the crystals of alloys and of oxides of a large number of other elements.

Since this special spin–spin force is fairly strong, we must ask why is it that ferromagnetic materials are ever found in a nonmagnetized state? Why is it that not every piece of iron is a permanent magnet? The answer is that on a microscopic scale ferromagnetic materials are *always* magnetized. A crystal of ordinary iron consists of a large number of small **domains** within which all the magnetic dipoles are perfectly aligned. But the direction of alignment varies from one domain to the next (Figure 33.5). Hence on a macroscopic scale, there is no discernible alignment because the domains are oriented at random. The sizes and shapes of the domains depend on the crystal. Typically, the sizes of domains range from a tenth of a millimeter to a few millimeters, although in a large, uniform crystal the length of a domain may be several centimeters. Figure 33.6 shows domains in a crystal of iron.

Domain

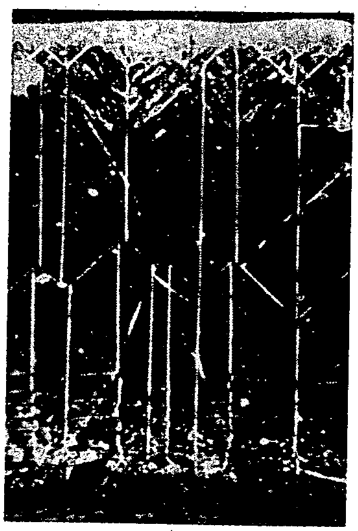


Fig. 33.6 Magnetic domains in a piece of iron. These domains are 0.1–0.3 mm across.

The formation of domains results from the tendency of the material to settle into the state of least energy (equilibrium state). The state of least energy for the spins would be a state of complete alignment. But such a complete alignment would generate a large magnetic field around the material, i.e., it would make the material into a (very strong) permanent magnet. Energetically, this is an unstable configuration, because there is a very large amount of energy in the magnetic field. The domain arrangement is a compromise. The spins align within the domains, but the domains do not align — the magnetic energy is then small because there is little magnetic field and the spin–spin energy is then also reasonably small because *most* adjacent spins are aligned.

However, if the material is immersed in an external magnetic field, all dipoles tend to align along this field. The domains will then change in two ways: those domains that already are more or less aligned with the field tend to grow in size at the expense of their neighbors and, furthermore, some domains will rotate their dipoles in the direction of the field.

If *all* the magnetic dipoles in a piece of ferromagnetic material align, their contribution to the magnetic field will be very large. For example, within a piece of magnetized iron, this contribution can be as much as 2.1 T, a rather strong magnetic field. Figure 33.7 is a plot of the actual magnetic field B in a piece of iron in a solenoid as a function of the magnetic field B_{free} contributed by the free current in the solenoid [$B_{free} = \mu_0 I_0 n$; see Eq. (31.16)]. If the value of B_{free} is 2.0×10^{-4} T, the value of B is about 1.0 T — the iron increases the magnetic field by a factor of about 5000!

The solid portion of the plot in Figure 33.7 was obtained by starting with a piece of unmagnetized iron (annealed iron), and subjecting it to an increasing magnetic field B_{free}. The dashed portion of the plot was obtained by gradually reducing the magnetic field B_{free} to zero, after it had reached the value indicated by the point P. The dashed plot shows

that even when B_{free} is reduced to zero, the iron retains some magnetization — the iron becomes a permanent magnet. Thus, the iron retains some memory of the magnetic field to which it was exposed earlier. Such a dependence of the state of a system on its past history is called **hysteresis.**

Hysteresis

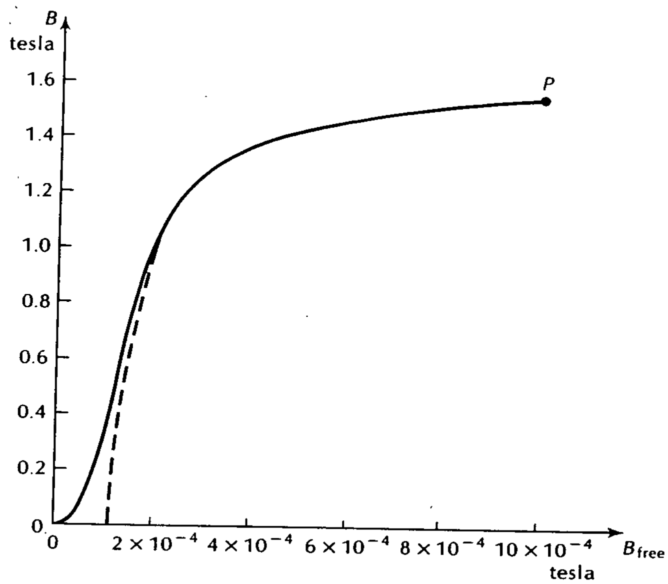


Fig. 33.7 Magnetic field B in annealed iron as a function of B_{free}. The solid curve shows B if the iron is immersed in an external magnetic field B_{free} that increases from an initial value of zero to a final value of 10×10^{-4} T. The dashed curve shows B if the external magnetic field is subsequently reduced to zero.

The hysteresis of a ferromagnetic material is due to a sluggishness in the rearrangement of the domains. Once the domains have become aligned in response to a strong external magnetic field, they tend to stay that way. If we remove the ferromagnetic material from the external magnetic field, the domains will suffer some rearrangement, but they will not lose their alignment completely. The remaining alignment gives the material a permanent distribution of magnetic dipole moments over its volume. The magnetic field of a permanent magnet is produced by these remaining aligned dipole moments.

As we saw in Section 33.2, the aligned dipoles effectively amount to a current running around the surface of the magnetized material (see Figure 33.4b). In a strong permanent magnet, this surface current may amount to several hundred amperes per centimeter of length of the magnet. The magnetic field produced by such a current distribution is obviously similar to that of a solenoid of finite length — the field lines emerge from the magnet at one end (the north pole) and reenter the magnet at the other end (the south pole); see Figures 33.8 and 33.9.

Incidentally, the maximum magnetization that a ferromagnetic material will retain after it has been removed from the external magnetic field depends on the temperature. The higher the temperature, the less the remaining magnetization. Above a certain critical temperature, called the **Curie temperature**, the magnetization disappears completely. For example, iron will not retain any magnetization if the temperature is in excess of 1043°C.

Curie temperature

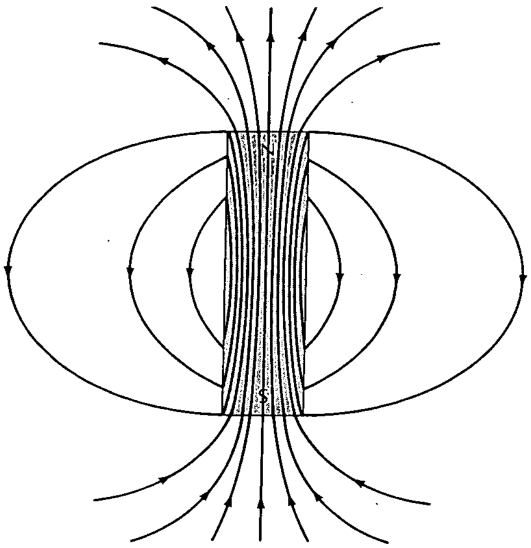


Fig. 33.8 Magnetic field lines of a permanent magnet.

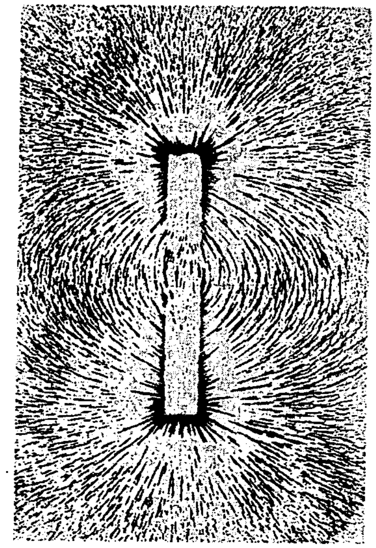


Fig. 33.9 Magnetic field lines of a permanent magnet, made visible by sprinkling iron filings on a sheet of paper.

33.4 Diamagnetism

In both paramagnetic and ferromagnetic materials the important effect is the alignment of *permanent* magnetic dipoles. This is quite analogous to the alignment of permanent electric dipoles in a dielectric. But we know that in some dielectrics the polarization is due to induced electric dipoles rather than permanent dipoles. Is it likewise possible for a material to acquire *induced* magnetic dipoles?

Diamagnetic material

In **diamagnetic materials** the magnetization arises from such induced magnetic dipoles. To see how the magnetic field can induce dipole moments in the atoms, imagine that a sample of some material is placed between the poles of an electromagnet which is initially switched off. If the electromagnet is now switched on, the external magnetic field must increase from its initial (zero) value to its final value. Thus, for a short while, the magnetic field will be time dependent and it will therefore induce an electric field within the sample. Let us consider the effect of this electric field on the motion of an electron. We will again pretend that classical mechanics applies to this problem.

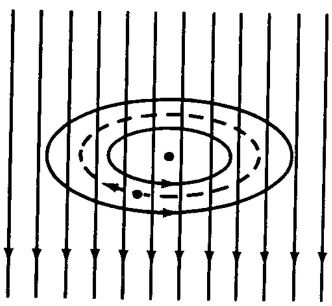


Fig. 33.10 Electron in a circular orbit around a nucleus immersed in an increasing magnetic field. The black circles indicate the induced electric field.

Figure 33.10 shows the orbit of an electron within an atom and also shows the increasing magnetic field. If the electron moves clockwise, as seen from above, the induced electric field (compare Example 32.4) will speed the electron up, giving it a larger orbital angular momentum and magnetic moment. The increment of angular momentum produces a magnetic field (within the orbit) that *opposes* the original magnetic field. This is obvious from Lenz' Law: the change in the motion of the electron amounts to an induced current, and the magnetic field associated with this current must be such as to oppose the original increasing magnetic field.

This argument establishes that induced magnetic moments reduce the strength of the magnetic field. The argument is quite general and applies to any kind of electron orbit and any kind of material. However, in paramagnetic and ferromagnetic materials the reduction of magnetic field due to induced magnetic moments is more than compensated by the increase of magnetic field due to alignment of permanent magnetic moments. If the material has no permanent magnetic moments, then the effect of the induced magnetic moments becomes noticeable and the material will be diamagnetic.

Diamagnetism is a very small effect. The following calculation gives some idea of the size of this effect. When the material is placed in a magnetic field $\mathbf{B}$, the electrons will experience a force $-e\mathbf{v} \times \mathbf{B}$ in addition to the usual electric force acting within the atom. Figure 33.11 shows the simple case of an electron in a circular orbit of radius r around a nucleus; the orbit is perpendicular to the magnetic field $\mathbf{B}$. If the nucleus produces an electric field $\mathbf{E}$, then the net force on the electron is $-e\mathbf{E} - e\mathbf{v} \times \mathbf{B}$. This force must match the product of mass and centripetal acceleration,

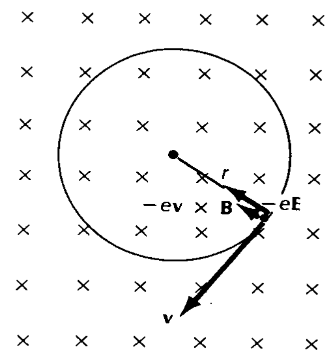


Fig. 33.11 Electron in a circular orbit around a nucleus immersed in a magnetic field. The centripetal force on the electron is the sum of the electric attraction of the nucleus and the magnetic force.

$$eE + evB = m_e v^2/r \tag{10}$$

In terms of the angular frequency of the motion, the equation of motion becomes

$$eE + e\omega rB = m_e \omega^2 r \tag{11}$$

Let us compare this with the equation of motion in the absence of the magnetic field (undisturbed atom, $B = 0$),

$$eE = m_e \omega_0^2 r \tag{12}$$

If we subtract Eq. (12) from Eq. (11), we obtain a relation between the frequencies ω and ω_0:

$$e\omega B = m_e\,(\omega^2 - \omega_0^2) \tag{13}$$

It is convenient to express this in terms of the increment of frequency,

$$\Delta\omega = \omega - \omega_0 \tag{14}$$

If the magnetic field is not excessively strong, $\Delta\omega$ will be small compared to ω_0 and hence

$$\begin{aligned} \omega^2 - \omega_0^2 &= (\omega_0 + \Delta\omega)^2 - \omega_0^2 \\ &= 2\omega_0\,\Delta\omega + (\Delta\omega)^2 \cong 2\omega_0\,\Delta\omega \end{aligned} \tag{15}$$

so that Eq. (13) becomes

$$e\omega B \cong 2m_e\omega_0\,\Delta\omega \tag{16}$$

Since ω and ω_0 are nearly equal, we can cancel them on both sides of this equation without introducing any additional errors. This leads to

$$\boxed{\Delta\omega = \frac{eB}{2m_e}} \tag{17}$$

Larmor frequency

This frequency is called the **Larmor frequency.** It tells us how much faster the electron will move around its orbit because of the presence of the magnetic field (of course, if the electron is initially moving in a direction opposite to that shown in Figure 33.11, then the electron will move *slower* by the same amount). Note that our calculation implicitly assumed that the orbital radius does not change as the magnetic field **B** is switched on. This assumption can be justified with an extra calculation that verifies that the work done on the electron by the induced emf changes the kinetic energy by just the amount required by the change of angular frequency at a fixed radius.

Corresponding to the change $\Delta\omega$ in the orbital frequency, there will be a change in the orbital magnetic moment. From Eq. (3),

$$\mu = \frac{evr}{2} = \frac{er^2\omega_0}{2} \tag{18}$$

Hence

$$\Delta\mu = \frac{er^2}{2}\,\Delta\omega \tag{19}$$

Dividing these equations into one another, we obtain an expression for the fractional change in the magnetic moment:

$$\frac{\Delta\mu}{\mu} = \frac{\Delta\omega}{\omega_0} \tag{20}$$

Let us insert some numbers. Typically the frequency of motion of an electron in an atom is $\omega_0 \cong 10^{15}$ s. If the magnetic field is fairly strong, say, $B = 1.0$ T, then

$$\Delta\omega = \frac{eB}{2m_e} = \frac{1.6 \times 10^{-19}\ \text{C} \times 1.0\ \text{T}}{2 \times 9.1 \times 10^{-31}\ \text{kg}}$$

$$= 8.8 \times 10^{10}/\text{s} \tag{21}$$

Consequently,

$$\frac{\Delta\mu}{\mu} = \frac{\Delta\omega}{\omega_0} = \frac{8.8 \times 10^{10}/\text{s}}{10^{15}/\text{s}} \cong 10^{-4} \tag{22}$$

that is, the magnetic moment only changes by about 1 part in 10^4. This gives an indication of the small size of the diamagnetic effect.

The diamagnetic characteristics of a material can be described by a relative permeability κ_m that indicates by what factor the magnetic field is changed [compare Eq. (8)]. In the paramagnetic case $\kappa_m > 1$, but in the diamagnetic case $\kappa_m < 1$.

Table 33.3 lists some diamagnetic materials and the corresponding values of κ_m. In all cases, the value of κ_m is very near to 1.

Table 33.3 PERMEABILITIES OF SOME DIAMAGNETIC MATERIALS[a]

Material	κ_m
Bismuth	$1 - 1.9 \times 10^{-5}$
Beryllium	$1 - 1.3 \times 10^{-5}$
Methane	$1 - 3.1 \times 10^{-5}$
Ethylene	$1 - 2.0 \times 10^{-5}$
Ammonia	$1 - 1.4 \times 10^{-5}$
Carbon dioxide	$1 - 0.53 \times 10^{-5}$
Glass (heavy flint)	$1 - 1.5 \times 10^{-5}$

[a] At room temperature (20°C) and 1 atm.

SUMMARY

Magnetic moment of orbiting electron: $\mu = \dfrac{e}{2m_e} L$

Permeability constant: $B = \kappa_m B_{free}$

Magnetic materials: paramagnetic: $\kappa_m \gtrsim 1$
ferromagnetic: $\kappa_m \gg 1$
diamagnetic: $\kappa_m < 1$

Ampère's Law in paramagnetic and diamagnetic materials:

$$\oint \frac{1}{\kappa_m} \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{free}$$

Larmor frequency: $\Delta\omega = \dfrac{eB}{2m_e}$

QUESTIONS

1. Show that the SI unit of magnetic moment ($A \cdot m^2$) is the same as joule per tesla (J/T).

2. How would you measure the magnetic moment of a compass needle?

3. A bar magnet has a north pole and a south pole. If you break the bar magnet into two halves, do you obtain isolated north and south poles?

4. If we regard the Earth as a bar magnet, where is the magnetic north pole?

5. Consider a closed mathematical surface enclosing one of the poles of a bar magnet. What is the magnetic flux through this surface?

6. It is possible to magnetize an iron needle by pointing it north and giving it a few blows with a hammer. Explain.

7. If you drop a permanent magnet on a hard floor, it can become partially demagnetized. Explain.

8. Why does a magnet attract an (unmagnetized) piece of iron?

9. If you sprinkle iron filings on a sheet of paper placed in a magnetic field, the filings orient themselves along magnetic field lines (see Figure 33.9). Explain.

10. Other things being equal, a horseshoe magnet produces a stronger magnetic field than a bar magnet. Why?

11. You can make a chain of paper clips by touching one end of a clip to the pole of a magnet, then touching the free end to another paper clip, etc. Explain.